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The Policy Choice and Economic Assessment of High Emissions Industries to Achieve the Carbon Peak Target under Energy Shortage—A Case Study of Guangdong Province

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Abstract: In recent years, due to the rise in energy prices and the impact of COVID-19, energy shortages have led to unsafe power supply environments. High emissions industries which account for more than 58% of the carbon emissions of Guangdong Province have played an important role in achieving the carbon peak goal, alleviating social energy shortage and promoting economic growth. Controlling high emissions industries will help to adjust the industrial structure and increase renewable energy investment. Therefore, it is necessary to comprehensively evaluate the policies of energy security and the investments of high emission industries. This paper builds the ICEEH-GD (comprehensive assessment model of climate, economy, environment and health of Guangdong Province) model, designs the Energy Security scenario (ES), the Restrict High Carbon Emission Sector scenario (RHS) and the Comprehensive Policy scenario (CP), and studies the impact of limiting high emissions industries and renewable energy policies on the transformation of investment structure, macro-economy and society. The results show that under the Energy Security scenario (ES), carbon emissions will peak in 2029, with a peak of 681 million tons. Under the condition of ensuring energy security, the installed capacity of coal-fired power generation will remain unchanged from 2025 to 2035. Under the Restrict High Carbon Emission Sector scenario (RHS), the GDP will increase by 8 billion yuan compared with the ES scenario by 2035. At the same time, it can promote the whole society to increase 10,500 employment opportunities, and more investment will flow to the low emissions industries. In the Comprehensive Policy scenario (CP), although the GDP loss will reach 33 billion yuan by 2035 compared with the Energy Security scenario (ES), the transportation and service industries will participate in carbon trading by optimizing the distribution of carbon restrictions in the whole society, which will reduce the carbon cost of the whole society by more than 48%, and promote the employment growth of 104,000 people through industrial structure optimization. Therefore, the power sector should increase investment in renewable energy to ensure energy security, limit the new production capacity of high emissions industries such as cement, steel and ceramics, and increase the green transition and efficiency improvement of existing high emissions industries.

Keywords: CGE; Guangdong; renewable; carbon peak; energy safety; economic impact

1. Introduction

According to the IPCC (Intergovernmental Panel on Climate Change, IPCC) 1.5 °C special report, the global annual total emissions must be cut in half by 2030 and must reach near-zero carbon dioxide emissions by 2050 [1]. In response to this goal, China proposes to strive to achieve the peak of carbon dioxide emissions by 2030 and achieve carbon neutrality by 2060. As one of the first low-carbon pilot provinces in China and one of the most economically developed regions in China, Guangdong should be at the forefront of the country in low-carbon transformation, industrial upgrading and green development. In 2021, China put forward the "Opinions on completely, accurately and comprehensively implementing the new development concept and doing a good job of carbon peaking and carbon neutralization [2], in which by 2030, the carbon dioxide emissions per unit of GDP will be reduced by more than 65% compared with 2005, the proportion of non-fossil energy consumption will reach about 25%, the total installed capacity of wind power and solar power will reach more than 1.2 billion kW, and the emissions of carbon dioxide will have reached the peak and begun to decrease steadily. The Guangdong Province also strives to continue to take the lead in the control level of carbon dioxide emissions per unit of GDP in the country. The Guangdong Province will achieve the peak of carbon emissions by 2030 and strive to be the first to reach the peak in the country.

The total energy consumption of the Guangdong Province in 2020 was 345 million tons of standard coal, and the growth rate of energy consumption during the 13th Five Year Plan period reached 2.74% [3]. According to the accounting of CEADs team, the total carbon emissions of the Guangdong Province in 2019 were about 585 million tons, and the growth rate of carbon emissions from 2015 to 2019 reached 3.27% [4]. At present, carbon emissions and energy consumption were still in the stage of rapid growth. In the future, the relationship between energy consumption, carbon emissions and the economy will need to be coordinated with policy interventions.

With the change in the international situation and the impact of the COVID-19 pandemic, there was great uncertainty in the prices of coal and natural gas, which will also have varying degrees of impact on the industry. In order to ensure energy security, governments of various countries restarted coal-fired power, and coal consumption increases instead of decreasing, which may bring some uncertainty to the peak carbon emissions. However, in the long run, carbon peak and carbon neutralization were medium and long-term strategies implemented by China. In the long run, the carbon peak will have a positive impact on GDP, which can promote industrial transformation, energy structure optimization, employment and GDP growth of the whole society. At the same time, the carbon peak was closely related to the sectoral restriction policies. Combined with the internal and external factors affecting the economy, the future policies will be flexibly adjusted according to the changes in the situation. It is important to use comprehensive policies to realize the balanced and high-quality development of energy, the economy and the environment. Many scholars generally study the low carbon path, carbon tax or emission trading policy, the impact of carbon peaking and carbon neutralization on economic and social development from the perspective of the goal of social constraints and the change in investment structure [5–7].

Research on the path and technology upgrade for the high emissions industries. For China's 2 °C and 1.5 °C scenarios, Xie [8] estimated that the carbon emissions from fossil energy combustion in 2050 should be 2.9 billion tons and 1.5 billion tons, respectively. Jiang [9] estimated that to achieve the 2 °C and 1.5 °C goals, carbon emissions need to be controlled at 3 billion tons and 590 million tons of negative emissions will need to be attainable in 2050. Duan [10] further evaluated that China needs to reach the peak in 2020 and reduce carbon emissions to 1–2 billion tons in 2050 to achieve the 1.5 degree goal. In terms of regional research, Feng Ren [11] has predicted that if Guangdong reaches the carbon peak before 2028, it needs to accelerate the clean and low-carbon transformation on the energy supply side, improve the electrification rate of construction, transportation, chemical industry and other industries, and strive to promote the transformation of energy structure from fossil energy to clean energy. Many scholars have studied the carbon peaking and neutralization paths [12–16], but few have evaluated the macroeconomic impact of carbon peaking and carbon neutralization, without considering the impact of carbon costs in peaking and neutralization paths. In particular, restricting the high emissions industries and renewable energy policies will affect the upstream and downstream sectors of the industrial chain to change and have a lasting economic impact.

Research on carbon tax and carbon trading. At present, the research on carbon emission reduction policies mainly includes technological progress and energy efficiency improvement, demand reduction, the improvement of management level and carbon pricing policy, of which carbon pricing policy mainly includes carbon tax and carbon trading market system. According to the report released by the World Bank in 2020, 61 carbon price mechanisms were being implemented in the world, with 31 carbon trading and 30 carbon taxes, respectively, covering 22% of global greenhouse gas emissions [17]. In model research, the carbon price was usually used to quantitatively analyze the cost and intensity of carbon emission reduction policies. According to the IPCC 1.5 special report, in order to achieve the 2-degree and 1.5-degree goals, the carbon price in 2050 needs to reach $45~1050 and $245~14,300/ton of CO_2, respectively [1]. Oshiro [18] used the AIM/Enduse model to analyze Japan’s carbon neutralization in 2050, and calculated that the cost of carbon emission reduction was as high as 2200 US dollars/ton. The EU studied to achieve carbon neutralization in 2050 based on PRIMES model, and the carbon price exceeded 350 euros/ton [19]. Climate works Australia studied a technology optimization model based on AUS times model, and found that for Australia to achieve carbon neutralization by 2050, the carbon price must reach 200~233 US dollars/ton [20]. Due to the different model framework, there was a large gap between emission reduction targets, technical level and policy options. In the research of carbon tax policy, Zhai [21] studied that when the carbon tax was 100 yuan/ton, Guangdong’s GDP will drop less than 0.5%, resulting in more than 1.2 million tons of carbon emission reductions, and suggested that Guangdong should adopt a carbon tax of 10–40 yuan through the multidimensional Carbon Policy (CMDCP) model based on CGE model. At present, these studies agree that carbon neutralization needs to be achieved through the policy means of carbon pricing, but they lack consideration for the impact of the carbon price on the economy and society, which will then be transmitted to the impact on the macro-economy and society [22–24].

Economic impact and carbon emission reduction. Lin [25] pointed out that industrial structure adjustment was the most effective means to reduce energy intensity from the perspective of the contribution rate of carbon neutrality to economic growth, and technology effect was the key to improve energy efficiency. Strategies such as increasing economic density, weakening administrative intervention and expanding and opening-up can better improve energy efficiency and promote the realization of carbon neutrality. SamMeng [26] used a new computable general equilibrium (CGE) model to gauge the effects of a national emissions trading scheme (ETS) on the Australian energy sector and the broader economy. The modelling results show that an ETS can reduce emissions effectively and with a relatively small impact on the overall economy. Zhang [27] used C-GEM model to study the path of China’s energy economy transformation under the vision of carbon neutrality, which will contribute to the high-quality development of China’s economy, although many scholars also use macroeconomic models and technical models to evaluate the optimal technological path, policies and measures must also be used to achieve the double carbon goal [22,23,28]. Spreafico [29], using the Life Cycle Assessment (LCA) method, assessed domestic environmental impacts for determining the carbon footprint of different alternative domestic components. Christopher [30] used CGE model findings to determine that without the Production Tax Credit, the Colorado policy of mandating renewable power generation is costly to state actors, with an implied cost of carbon of about $17 per ton of CO_2.

How to consider the impossible triangle of safety, efficiency and cleanliness, and how to position the development of the high emissions industries under the current international situation and the background of the COVID-19 under the goal of carbon peak and carbon neutrality, in which not only the safe supply of energy should be ensured, but also the sustainable economic development will be achieved.

The CGE model is an energy economy model based on the general equilibrium theory. It describes the joint and several effects on the restriction of departments under the policy disturbance by analyzing the input-output relationship between departments. The realization of the goal of carbon peaking and carbon neutralization will be a major economic and social change, which will significantly change the current industrial system and energy system, especially for the enterprises in the upstream and downstream of the industrial chain. The general energy technology model rarely describes the impact of carbon peak and carbon neutralization process on the economic system. The CGE model can link the relationship between macro-economy and carbon emissions, energy consumption and industrial development, so as to quantitatively analyze the changes of industrial structure and energy structure in the Guangdong Province under the policy of carbon peak.

In order to study the impact of different policy scenarios on the economic and social environment at different carbon peak targets, this study builds a CGE model to evaluate the impact of the implementation of different policy tool parameters, to further analyze the development path of the high emissions industries. It is necessary to research the relationship between the target indicators of the implementation of carbon peak and other important macro variables, and to simulate how the development path of different high emissions industry projects affects the overall economic development under the constraint of the carbon peak goal.

By constructing a CGE model of the Guangdong Province, this paper simulates the impact of restricting the policies of high emissions industries and renewable energy policies on the macro-economy. It further effectively identified the impact of high emissions industries on the carbon peak goal and energy security. While ensuring the realization of economic growth and carbon emission reduction goals, it also takes into account employment stability and high-quality economic development, so as to support policy makers to make industrial policies and investment decisions that meet the requirements of the current stage.

In this study, the first section is background introduction, literature review and the purpose and innovation. The second section is the introduction of our research methodology, the third section is the main parameter setting and scenario setting of the model, the fourth section is the main results of the model, and the fifth section is the conclusion and policy recommendations

2. Methodology

Based on the input-output table [31] of the Guangdong Province in 2017, combined with the data of energy balance table and Industrial Employment Statistical Yearbook, the installed capacity of power generation technology, power generation structure, power generation cost and other data of the Guangdong Province in 2017 [3,32,33], this study constructs the integrated assessment model of climate, economic, environment and Health (ICEEH-GD) of the Guangdong Province. The model consists of five modules: production sector, resident sector, government sector, international sector and inter-provincial trade. The model architecture was shown in Figure 1. The main model structure and department association references in the model refer to Wang [34].

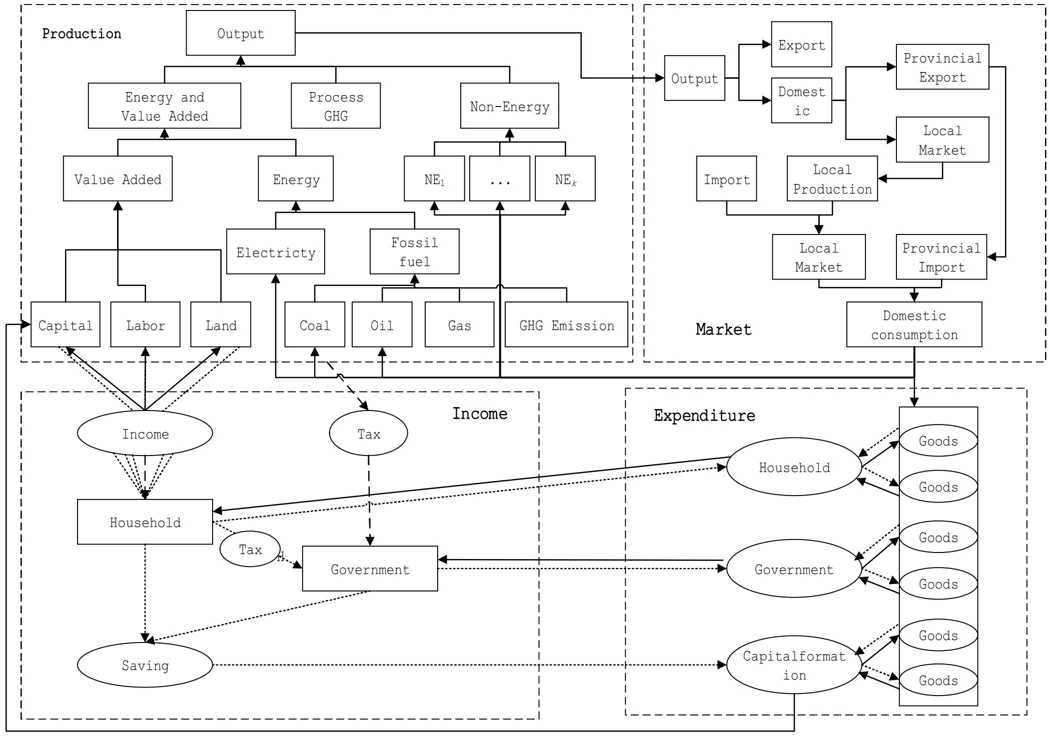

Figure 1. Model architecture.

2.1. Production Sector

There were 33 production sectors in the model, including 7 energy sectors (Table 1). Constant elasticity of substitution (CES) was used in the activities of all sectors. Input parameters include intermediate products, energy commodities, initial labor and capital. Based on the energy balance table, energy commodities were divided into material use and fuel use.

Table 1. Classification of production sectors.

No.	Code	Sector	No.	Code	Sector
1	AGR	Agriculture	18	I_S	Iron and Steel
2	CMN	Mining and Washing of Coal	19	NFM	Nonferrous Metal Smelting
3	OIL	Extraction of Petroleum	20	MPD	Metal Products
4	GAS	Extraction of Gas	21	MCH	Mechanical Manufacturing
5	ONM	Mining and Dressing of Other Ores	22	ELP	Manufacture of Electrical Machinery
6	FOD	Manufacture of Food	23	ELE	Electric Power and Heat Power
7	TEX	Textiles	24	GDT	Production and Supply of Gas
8	LUM	Manufacture of Furniture	25	WTR	Production and Supply of Water
9	PPP	Papermaking and Paper Products	26	CNS	Construction industry
10	OMF	Other Manufactures	27	TRL	Road Transport
11	P_C	Petroleum, Coal Processing	28	TRD	Railway Transportation
12	COK	Coking	29	TPL	Urban public Transport
13	CRP	Chemical industry	30	TWT	Water Transport
14	CMT	Cement	31	TAR	Air Transport
15	ONM	Other non-metallic manufacturing	32	TPP	Other Transportation
16	GLS	Glass manufacturing	33	CSS	Service
17	ETW	Ceramic manufacturing			

According to the input-output table structure and Dai [35] in the model, the power and heat production and supply industry was re-divided into seven sub sectors: thermal power unit, natural gas generator unit, oil generator unit, wind power and solar power unit, nuclear power unit, hydropower unit and garbage, biomass and other generator units. The seven sub sectors participate in the input-output calculation separately. It was summarized as the data of the power sector to investigate the impact of new energy development on the economic development and energy consumption of the Guangdong Province.

2.2. Residential Sector

Residents were the final consumer sector. The residential sector will generate terminal consumption demand for products from high emission industries and other industries, and the demand for terminal consumption will lead to production and emissions of high emission sectors. Residents obtain factor income and government transfer payment income, and all income obtained by residents was used for consumption or investment. The investment volume assumption was the same as the GDP growth rate of the Guangdong Province from 2017 to 2030. The resident sector maximizes the consumption utility under the restriction of income level and commodity price.

2.3. Government Sector

Government sectors were also final consumption sectors, and government sectors include tax revenue. The government is not only a terminal consumption department, but also undertakes the related functions of tax transfer payment, so as to more efficiently allocate the capital needs of the whole society. Both government and resident sectors use the Cobb-Douglas function to transfer tax revenue from government sectors and provide public services for residents.

2.4. International Trade

This model adopts the small country hypothesis; the economies in the model will not have a significant impact on the world economy. The energy prices of international commodities were rising year by year, and the rest were fixed at the base year prices. At the same time, the proportion of various products in international trade was fixed.

2.5. Inter Provincial Trade

The important feature of the two regional CGE model was to increase the trade module between Guangdong (GD) and other regions of China (ROC, rest of China). The trade between the two regions adopts the Armington equation to distinguish the products produced in Guangdong and other regions in China and describe them with the CES function. The specific formula was:

$$Max\pi_i = p_i \times Q_i - \left[p_i^{md} \times Q_i^{md} + \sum p_i^{inf} \times D_i^{inf}\right] \tag{1}$$

s.t.

$$Q_i = \alpha_i \times \left(\delta_i^{md} \times Q_i^{md^{-\rho_i}} + \sum \delta_i^{inf} \times Q_i^{inf^{-\rho_i}}\right)^{-\frac{1}{\rho}} \tag{2}$$

$$\text{and } Q_i^{md} = \left[\frac{\alpha_i^{-\rho_i} \times \delta_i^{md} \times p_i}{p_i^{md}}\right]^{\frac{1}{1+\rho_i}} \times Q_i \tag{3}$$

$$D_i^{inf} = \left[\frac{\alpha_i^{-\rho_i} \times \delta_i^{inf} \times p_i}{p_i^{inf}}\right]^{\frac{1}{1+\rho_i}} \times Q_i \tag{4}$$

where

π_i total profit of *i* products

Q_i	Total demand for *i* products
D_i^{inf}	Total amount of *i* products transferred from other regions
p_i	The price of *i* products
p_i^{inf}	Price of *i* products transferred in from other regions
α_i	Production efficiency parameters of *i* products
$\delta_i^{inf}, \delta_i^{md}$	Proportion of products transferred in and self-produced
ρ_i	Substitution elasticity parameters of self-produced products within the province and inter provincial transfer in

2.6. CO_2 Emission Reduction

This model considers CO_2 emissions from fossil fuel consumption. Carbon emission reduction was mainly based on three alternatives [35]:

Fuel substitution: with the rise in carbon prices, the production sector may choose natural gas or other non-fossil energy with less carbon dioxide emissions.

Factor substitution: due to the rising price of carbon emissions, the production sector may choose factor production links with lower total cost, such as the mutual substitution of labor, raw materials and capital, to reduce carbon emissions through factor substitution.

Product substitution: as the price of high-carbon products rises, the consumption of residential sectors decreases, and indirectly reduce the production of high-carbon products to reduce carbon dioxide emissions.

2.7. Optimal Allocation Module of Carbon Emission Rights

This model endogenously generates the loss of output revenue caused by the sector to achieve a given emission reduction, the marginal emission reduction cost of the sector, by setting an exogenous carbon emission cap for the sector. In the simulation of carbon trading scenario, the sectors included in the scope of carbon trading were traded, so as to balance the average marginal emission reduction cost (carbon price) of the sectors involved in carbon trading.

The carbon emissions trading module in this study was mainly reflected in the implementation of the total carbon emissions limit and the trading system between sectors. The model assumes that the revenue generated from the government's sale of carbon emission quotas was returned to the residential sector through transfer payments. As shown in Figure 2, C_1 and C_2 were the sectoral demand curves for carbon quotas. The horizontal axis in the figure represents the quota of the sector, and the vertical axis represents the marginal emission reduction cost of the sector. When carbon trading was allowed, sector 1 tends to buy the carbon quota of ΔQ_1 from the carbon market, and sector 2 tends to sell the carbon quota of ΔQ_2 to the carbon market. ICEEH-GD model will find a new equilibrium point to enable all sectors to participate in the carbon market, and the carbon market will be cleared. Its formulas were shown in Equations (5) and (6).

$$\sum_s \Delta Q_s = \sum_b \Delta Q_b \tag{5}$$

$$\sum_s \int_{P_s}^{P'} C_s(p)dp = \sum_b \int_{P'}^{P_b} C_b(p)dp \tag{6}$$

where

ΔQ: sectoral carbon trading volume

$C(p)$: sectoral demand function for carbon quotas

P: sectoral marginal emission reduction costs

S: S = $\int_P^{P'} C(p)dp$, the income paid by the government for the transfer of carbon emission rights to the residential sector

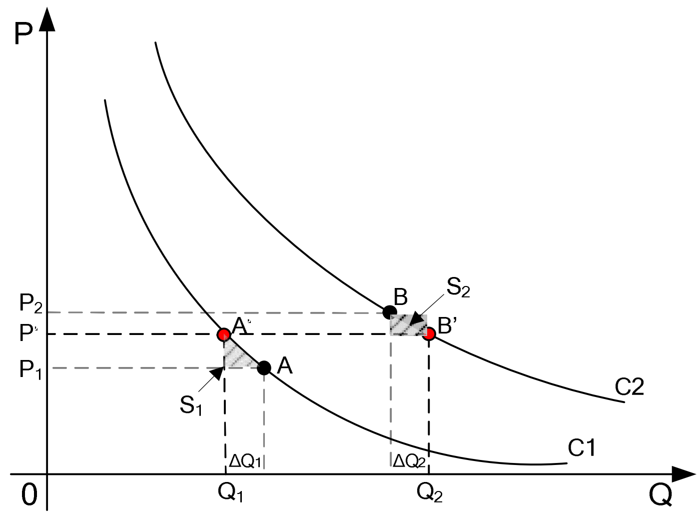

Figure 2. Optimal allocation mechanism of carbon emission rights in the whole society.

3. Model Parameters and Scenario Settings

3.1. Database

The input-output table was an important data source for building the social accounting matrix (SAM) and for modeling the relationship between departments and sub industries in the CGE model. The data are based on the latest input-output table of 147 departments in Guangdong Province in 2017 released by the Bureau of statistics of the Guangdong Province. The energy consumption of 33 departments in the Guangdong Province is sorted out from the energy balance table. Among them, the output value, added value, investment, consumption and other indicators of each department or industry in the CGE model are all in the unit of value, while the actual energy consumption and CO_2 emissions are in the form of physical quantities. In order to increase the accuracy of future energy consumption, power consumption and carbon emission prediction, it is necessary to check the total energy consumption and the value of energy consumption in the current year according to the energy balance table to obtain the average energy price of different energy varieties in the current year, and then convert the energy consumption and carbon dioxide emissions of various departments or industries according to the input-output table and energy carbon emission factors. The CO_2 emissions of 33 departments are calculated by the IPCC recommended method, that is, the CO_2 emissions are calculated by multiplying the fossil energy consumption by the carbon emission coefficient and then multiplying by the carbon oxidation rate.

3.2. Setting of GDP and Population Growth

The setting of investment and population growth rate was shown in Table 2. The investment growth rate refers to the GDP growth rate in the 14th five-year plan for national economic and social development of the Guangdong Province and the outline of the long-term goals for 2035 [36]. By 2035, the GDP will increase by more than 100% compared with 2020, and the GDP growth rate from 2026 to 2035 was set to be 5.5%. The population growth rate refers to the population growth rate in the population development plan of the Guangdong Province (2017–2030) [37], and the population growth rate was adjusted according to the results of the seventh census, and the population will not increase after reaching the peak around 2035.

Table 2. population and investment growth rate settings in Guangdong Province.

Year	2021–2025	2026–2030	2031–2035
GDP growth	6%	5.5%	5.5%
Population growth	0.9%	0.45%	0.15%

3.3. Power Installation Setting

According to the expected approval progress of short-term and medium and long-term power projects, the installed capacity data from 2017 to 2020 were checked, and the installed capacity of the Guangdong Province in 2025 and 2035 was studied with reference to the 14th five-year plan for energy and power development in the Guangdong Province, as shown in Table 3. It can be seen that the total installed capacity was still increasing from 2020 to 2035, with an average annual growth rate of 5.8%. Among them, the installed capacity of coal-fired power has increased by 1.3% annually, but the total installed capacity of coal-fired power has reached the upper limit between 2025 and 2030. The installed capacity of gas and electricity increases by 6% annually, and the installed capacity will reach the upper limit around 2030. The installed capacity of wind power increased by 17.3% annually, and that of nuclear power increased by 3.3% annually. The hydropower capacity in Guangdong was basically saturated, maintaining a stable installed capacity of 9.26 million kW. Biomass power generation and other installed capacity increased by 7.9% annually, and photovoltaic installed capacity increased by 13.7% annually. Pumped storage energy was mainly nuclear power, wind power, photovoltaic power, etc., as the energy storage regulation power supply, the installed capacity continues to grow, with an average annual growth of 7.5%, and the pumped storage energy was not included in the calculation of power generation to set the power supply and demand balance.

Table 3. Power installed capacity of various energy types in the Guangdong Province from 2017 to 2035 (GW).

Year	Coal	Gas	Wind	Nuclear	Hydro	Biomass	Solar	Total
2017	61.00	15.70	3.35	10.46	8.47	0.89	3.32	109.59
2020	64.27	28.38	5.65	16.14	9.26	2.75	7.97	141.72
2025	79.89	59.38	26.00	18.54	9.26	4.60	28.00	235.35
2030	79.89	68.38	42.00	24.34	9.26	6.60	42.00	289.35
2035	77.64	68.38	62.00	26.34	9.26	8.60	55.00	328.90
Average growth rate	1.3%	6%	17.3%	3.3%	0%	7.9%	13.7%	5.8%

3.4. Scenario Settings

The model itself was to simulate the effect of policy constraints and driving variables. The economic growth of Guangdong simulated by the model was a dynamic evolution model driven by investment. The growth of total investment and the investment increment of each sub industry sector were exogenous. The total investment was allocated according to the capital return rate of each industry in the previous year within the model. In the process of producing products, various industrial sectors will use energy and produce carbon emissions. The model assumes that all the products produced in that year were used for capital, consumption, import and export, and all products in the market were balanced and cleared. Under the equilibrium constraint of multivariate, the model can solve the equilibrium solution.

As shown in Table 4, we have set three scenarios, ES, RHS and CP, to study the impact of new energy policies and restrictions on high emissions industries on the macro-economy of Guangdong Province. According to the changes of different control variables, the relationship between the explanatory variable and the explained variable was discussed. Since the carbon emissions peaked, it means that the carbon dioxide emissions in the Guangdong Province no longer increased and began to decline after reaching the peak; in order to study and judge the peak in 2030 and the trend after reaching the peak, the target year of the model was set as 2035. Further, according to the model prediction data of the Guangdong Province from 2020 to 2035, this paper empirically discusses the effect of the total carbon policy conditions at different control time points after the implementation of the carbon peak policy in the Guangdong Province, and analyzes the adverse impact of the carbon peak time node. By looking for the estimator of causality caused by the peaking policy, evaluating the impact effect, and supporting the decision-making and deployment of relevant sectors in the province. The simulation results guide the guidance strategies for sector investment decisions and minimize the impact on the macro-economy, employment, sector added value, sector output and product output when achieving the national carbon peak goal, so as to achieve the carbon peak and the transformation of economic and social structure in a relatively stable and orderly direction.

Table 4. policy scenario description and parameter settings.

	Scenario Description
Energy Security Scenario (ES)	Ensure the safety of power supply, and adopt more coal and gas power to meet the new power consumption demand. Adopt moderate carbon restrictions on traditional high carbon emission sectors to achieve the goal of reaching the peak of carbon emissions in the whole society by 2030 (reaching the carbon peak in 2029).
Restrict High Carbon Emission Sector Scenario (RHS)	To ensure the safety of power supply, on the premise of ensuring power supply, vigorously develop renewable energy to replace coal and gas power. Adopt strict carbon restrictions on traditional high carbon emission sectors, reaching the peak two years ahead of the safe development scenario (reaching the carbon peak in 2027).
Comprehensive Policy scenario (CP)	To ensure the safety of power supply, on the premise of ensuring power supply, vigorously develop renewable energy to replace coal and gas power. Adopt stricter carbon emission limits for the whole society, and adopt the principle of minimum carbon price to trade carbon emission limits for the whole society, reaching the peak two years ahead of the RHS scenarios (reaching the carbon peak in 2025).

The Energy Security (ES) scenario, the Restrict High Carbon Emission Sector (RHS) scenario and the comprehensive policy (CP)scenario will peak in 2029, 2027 and 2025, respectively. At the same time, according to the national goal of reducing carbon intensity by 60–65% in 2030 compared with 2005, the Guangdong Province will complete the goal ahead of schedule, and reduce carbon intensity by 65–70% by 2030 compared with 2005, At the same time, considering the situation that Guangdong's carbon intensity decreased by 20.5% during the 13th Five Year Plan period, the carbon intensity was expected to decrease by about 17% during the 14th Five Year Plan period due to the launch of major petrochemical projects and the limited potential space for energy structure adjustment. The scenario parameter settings at different time nodes of carbon peak were shown in Table 4.

Under the comprehensive policy scenario (CP), after carbon restrictions were imposed on the whole society, each sector will be allocated according to the principle of minimizing the cost of using carbon resources in the whole society. Each sector will optimize the use of total carbon emissions, and each industry sector will optimize the allocation and use of carbon quotas according to the transmission of carbon prices in each production sector, so all sectors will be affected by the carbon price in the production process.

4. Results and Discussion

4.1. CO_2 Emissions

4.1.1. Total Social Carbon Emissions

As shown in Figure 3, under the security development (ES) scenario, the whole society will reach its peak in 2029, with a peak of about 682 million tons. In 2030, carbon emissions will be 48 million tons higher than those under the RHS scenario and 76 million tons higher than those under the CP scenario. The peak release times of the three scenarios were 2029, 2027 and 2025, respectively. By 2035, the CO_2 emissions of the three scenarios will drop to 600, 570 and 540 million tons.

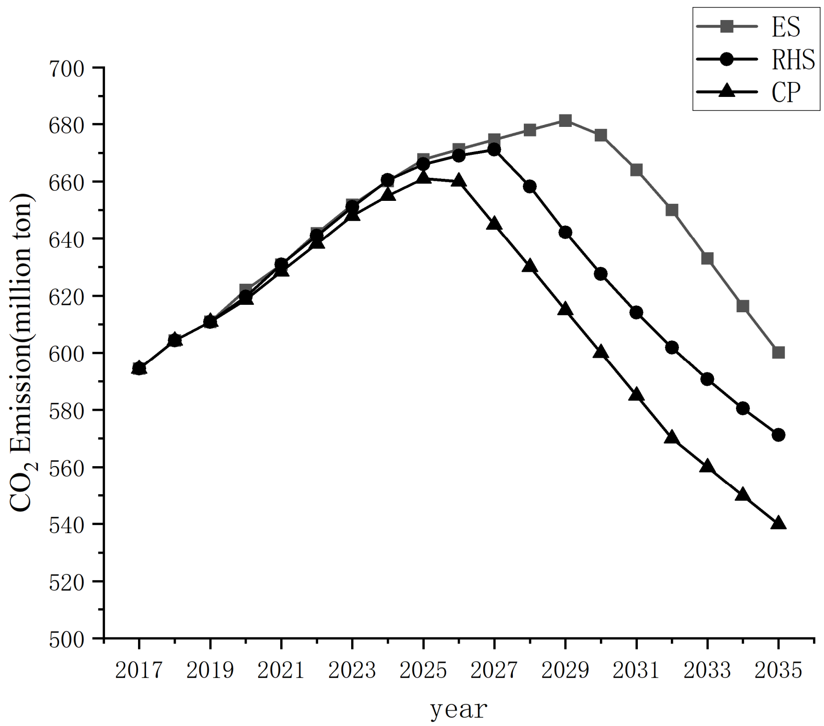

Figure 3. total carbon dioxide emissions under different scenarios.

4.1.2. CO_2 Emissions by Sector

As shown in Figure 4, by 2035, the sectors with the largest carbon emissions under the security development scenario (ES) were the power sector (116.1 million tons), the cement sector (86.3 million tons), the steel sector (38.9 million tons), the service industry (38.7 million tons), ceramics (29.0 million tons), and chemical industry (25.4 million tons), The carbon emissions of these six sectors account for 55.7% of the total social carbon emissions. Compared with the security development (ES) scenario by 2035, the sectors with the most carbon emissions reduction were electricity (−12.57%), paper industry (−19.29%), textiles (−19.29%), cement (−19.29%), steel (−19.29%), and ceramics (−19.29%) under the RHS scenario. Compared with ES scenario, the sectors with the most carbon emissions reduction were cement (−31.56%), electricity (−12.59%), and steel (−14.16%) Ceramic (−8.61%) under the CP scenario. Under the CP scenario, the carbon emissions of the chemical industry, paper industry, textile industry and other non-metallic industries rise instead of fall. Under the scenario of optimal allocation of the whole society, the cost of carbon reduction in these three sectors was high, and carbon emission quotas can be purchased from other low carbon reduction cost sectors, so the carbon emissions have increased.

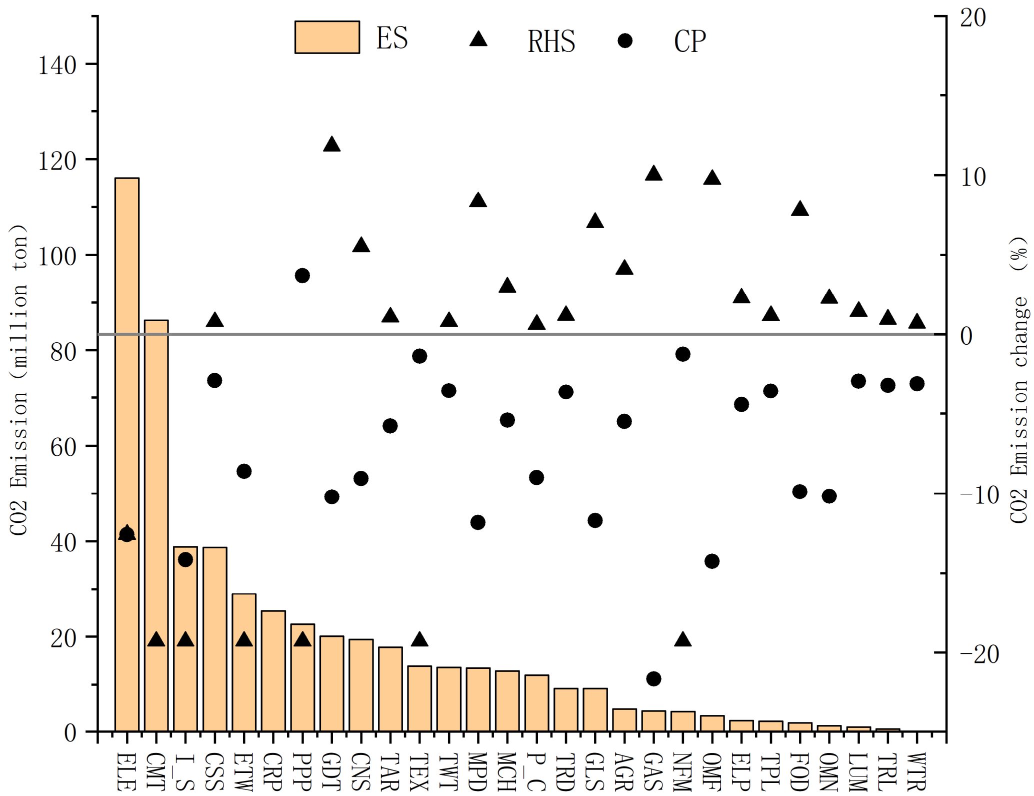

Figure 4. Carbon emissions of ES scenarios in 2035 (Left y-axis) and carbon emissions changes in RHS scenario and CP scenario compared with ES scenario (right y-axis).

Under the ES scenario, in order to ensure energy security and economic development, the high emissions industries undertake carbon emission quotas, other sectors jointly bear the remaining carbon emission limits and jointly achieve the carbon peak goal in 2029, so the carbon emissions of high carbon emissions industries are relatively high. Under the RHS scenario, the carbon emissions of the high emissions industries are strictly limited. High emissions industries afford heavy responsibility for carbon emission reduction to achieve the carbon peak goal in 2027. Therefore, the carbon emissions of these sectors will decrease. At the same time, amount of carbon emission space will be released for other sectors, so other sectors carbon emission will increase. Under the CP scenario, since the carbon peak is advanced to 2025, the total carbon emission limit of the whole society is more stringent, so almost all sectors have lower carbon emissions than in the ES scenario. However, through the optimized allocation of carbon emission limits, sectors with lower emission reduction costs can undertake more carbon emission reduction tasks, and release carbon emission space for high carbon emissions industries.

The carbon peak time of the respective department is shown in Table 5. In the ES scenario, the peak time of high emissions industrial industries will be from 2029 to 2031, while in the RHS scenario and CP scenario, it will be advanced to 2026 to 2027. Since there are no new coal-fired power plants in the Guangdong Province, the carbon emission of electric power has reached the peak in 2017.

Table 5. Carbon peak time of high emissions industries in different scenarios.

Sector	ES		RHS		CP	
	Peak Time	Emission	Peak Time	Emission	Peak Time	Emission
Unit	Year	Million ton	Year	Million ton	Year	Million ton
ELE (Electricity)	2017	196	2017	196	2017	196
CMT (Cement)	2029	95.5	2027	88.5	2025	75.5
IS (Iron & Steel)	2031	43.0	2027	39.9	2026	36.5
ETW (Ceramic)	2031	32.7	2027	29.9	2026	28.0
PPP (Papermaking)	2029	26.9	2027	23.3	2034	23.5
PC (Petroleum, Coal Processing)	2019	22.7	2019	22.7	2019	22.7
TEX (Textiles)	2030	16.1	2027	14.3	2026	14.0
NFM (Nonferrous Metal Smelting)	2030	4.8	2027	4.3	2026	4.1

4.2. Energy Structure

The total energy consumption and structure was shown in Figure 5. In 2017, coal accounted for 30%, oil accounted for 33%, natural gas accounted for 15%, and transferred power and primary power accounted for 22%. Under the RHS scenario, by 2035, the proportion of coal and oil consumption will decrease, the proportion of natural gas consumption will increase, and the proportion of purchased electricity will increase. Compared with ES Scenario, by 2035, the proportion of coal consumption will drop from 18% to 8% in the transition scenario and 6% in the deep transition scenario. The proportion of oil consumption should be controlled at about 30%. The proportion of natural gas consumption rose from 19% to about 22%. The proportion of transferred in power and primary power increased from 36% to 39% in RHS scenario and 45% in CP scenario.

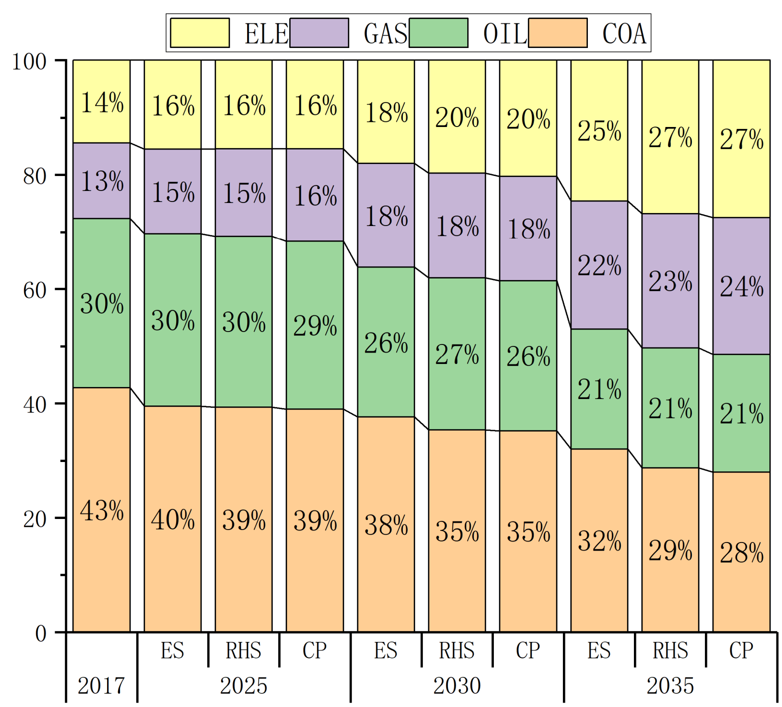

Figure 5. changes in energy structure under different scenarios.

From the perspective of the total power consumption of terminals, the total power consumption of ES scenario is 607 billion kwh in 2017 and will increase to 1080 billion kwh in 2035. However, under the RHS and CP scenarios, the total power consumption of the whole society will increase compared with the ES scenario by restricting the two high-tech industries and vigorously developing renewable energy. In 2035, the total power consumption of RHS scenario and CP scenario will increase by 2.9% compared with the ES scenario.

4.3. GDP Change

4.3.1. GDP Change in the Whole Society

The GDP growth rate under the three scenarios was shown in Figure 6. Under the ES scenario, the GDP of the whole society will increase to 17,900 billion yuan by 2030, and will increase to 22,600 billion yuan by 2035. From the comparison of the GDP of each scenario, compared with the ES scenario, the GDP of the RHS scenario and the CP scenario before reaching the peak was higher than that of the ES scenario, about 8 billion yuan higher. After reaching the peak, due to the high carbon emission limit, the GDP was gradually lower than that of the ES scenario. After 2032–2033, the GDP loss starts to decrease step by step, and the gap between GDP narrowed. By 2035, the GDP of the RHS scenario was about 8 billion yuan higher than that of the ES scenario, the GDP of CP scenario was still about 33 billion yuan lower than that of ES scenario. It can be seen that the loss of GDP was the comprehensive result of multiple factors. Carbon emission limits will significantly affect the carbon cost of sector production, resulting in sector losses. However, the adjustment of industrial structure and power structure will reduce the carbon production cost of the sector, thus alleviating the loss of GDP.

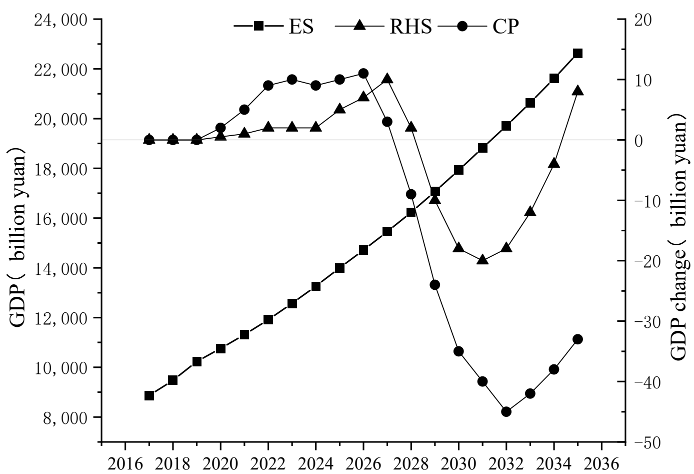

Figure 6. Change trend of GDP under ES scenario (left y-axis) and GDP change in RHS and CP scenario compared with ES scenario (right y-axis).

4.3.2. Changes in Value Added of Sub Sectors

As the investment and employment of the sector change, the actual output and added value of the sector will also change. Under the security development (ES) scenario, the sectors with the highest added value in 2035 will be the service industry, electronic information, agriculture, machinery manufacturing, chemical industry, construction and textile industries.

As shown in Figure 7, by 2035, compared with the security development (ES) scenario, the two highs (RHS) scenario will reduce the added value of industries such as textile (−7.88 million yuan), papermaking (−12.0 million yuan), cement (−9.49 million yuan), ceramics (−9.43 million yuan), steel (−11.7 million yuan), and will increase the chemical industry (55.4 million yuan), and machinery manufacturing (0.95 million yuan).

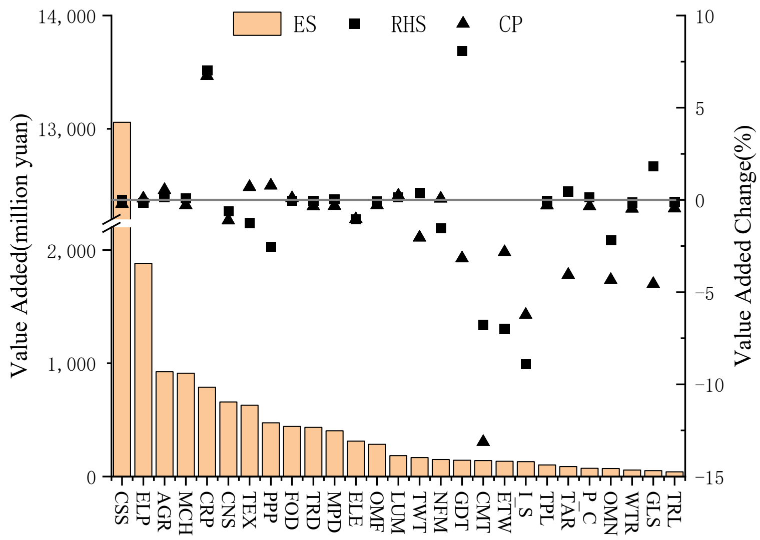

Figure 7. Value added of ES scenarios in 2035 (left y-axis) and value add changes in the RHS scenario and CP scenario compared with the ES scenario (right y-axis).

4.3.3. Cost of Carbon Emission Reduction in the Whole Society

The average cost of carbon emission reduction in the whole society was shown in the Figure 8. It can be seen in 2020, the cost of carbon emission reduction in the whole society under the ES and CP scenarios is about 600~700 yuan/ton of carbon, while the cost of carbon emission reduction in the ES scenario with the comprehensive implementation of emission reduction in the whole society is about 150 yuan/ton of carbon, which will slowly rise to 750~780 yuan/ton of carbon by 2025. In the ES scenario, the cost of carbon reduction rises rapidly increase to 5380 yuan/ton by 2035. In the RHS scenario, the average cost of carbon reduction in the whole society is lower than that in the ES scenario, about 4170 yuan/ton by 2035, due to the higher carbon restrictions in the two high-tech industries and the release of carbon emission reduction space in other industries. In the CP scenario, the cost of carbon emission reduction will reduce significantly to 2820 yuan/ton by 2035 due to the comprehensive policy, the cost of carbon emission reduction in the whole society has been optimized, and the departments with lower emission reduction costs bear more carbon emission reduction shares, reducing the average cost of carbon emission reduction in the whole society.

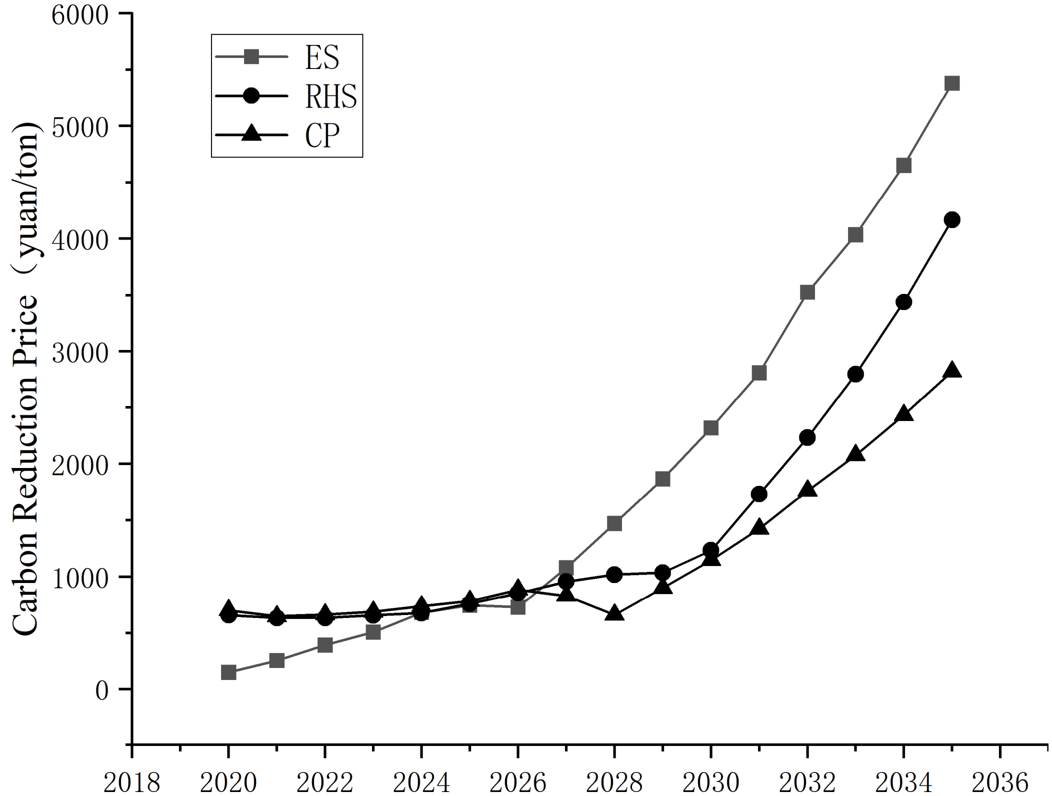

Figure 8. Carbon reduction price in different scenarios.

The whole society carbon emission reduction cost of CGE model refers to the marginal carbon emission reduction cost, which means the price of the last ton of carbon paid by this department to reduce carbon emissions under the carbon restriction. Therefore, compared with the actual carbon price, its meaning includes not only the carbon emission reduction cost, but also includes the loss of added value brought by carbon emission reduction.

4.4. Employment

At different peak times, investment in different sectors will change, prompting employment in different sectors to change. The number of employed people in Guangdong Province in 2017 was about 63.5 million. Under the two scenarios, it rose rapidly to about 68.5 million by 2025. Then, due to the slowdown of population growth, the number of employed people also showed a slow growth trend, reaching about 69.5 million by 2030 and about 70 million by 2035.

Figure 9 shows the employment impact under different scenarios. By 2035, compared with the security development (ES) scenario, the employment in the restricted two high (RHS) scenario will shift more from power, cement, construction, ceramics and other non-metallic industries to agriculture, electronic information, service, machinery manufacturing, food manufacturing and other industries by 2030. By 2030, compared with the security development (ES) scenario, the sectors with the largest decline in employment in the restricted two highs (RHS) scenario were cement (−3.8%), construction (−0.6%), ceramics (−2.2%), other non-metallic industries (−12.3%) and aviation (−3.4%), with a decrease of 14,700, 17,700, 7900 and 11,000, respectively, while the sectors with the largest increase in employment were agriculture (0.6%), electronic information (0.2%), service industry (0.1%), chemical industry (1.3%) and textile industry (0.3%), with an increase of 105,000, 16,300, respectively by 2030; 9400 people, 28,600 people, 6800 people. As far as the whole society was concerned, the situation of restricting the two highs will promote the employment of the whole society than the security development scenario. From the perspective of employment, carbon emissions limit will affect the added value of sectors. Therefore, under the RHS scenario, compared with the ES scenario, some jobs are lost in the high emissions industries, and these jobs are transferred to other industries. Under the CP scenario, through comprehensive measures, the allocation of carbon emission allowances is optimized, the added value and employment of most sectors have increased. By 2035, the whole society will increase 10,500 jobs, and the comprehensive policy scenario will increase 104,000 people.

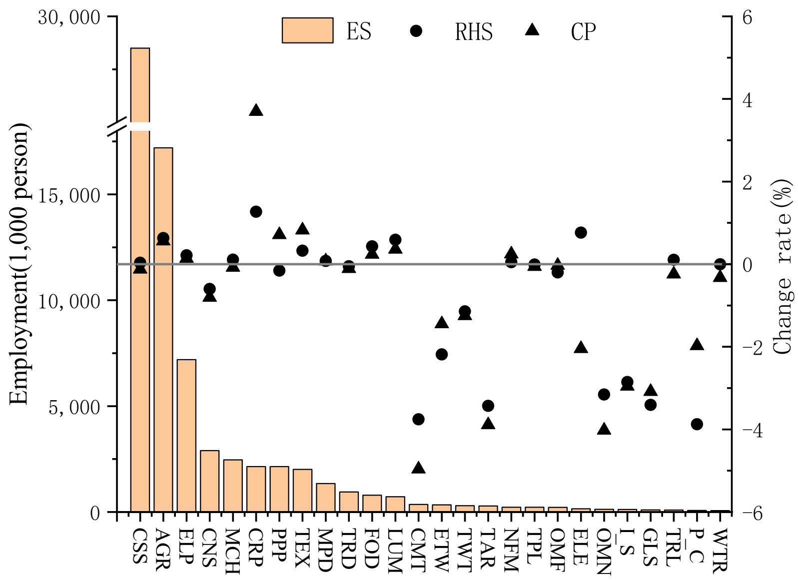

Figure 9. Employment of ES scenarios in 2035 (left y-axis) and employment changes in the RHS scenario and CP scenario compared with the ES scenario (right y-axis).

4.5. Carbon Intensity

It can be seen from the Figure 10 that under the condition of constant total investment, the carbon intensity of the ES scenario shows a trend of slow first and then fast. By 2025, the carbon intensity of ES, RHS and CP scenarios will be reduced by −17.5%, −17.6% and −17.9%, respectively, compared with 2020. The carbon intensity of 2030 will be reduced by −34.8%, −39.2% and −41.7%, respectively, compared with 2020. The carbon intensity of 2035 will be reduced by −54.1%, −56.2% and −58.4%, respectively, compared with 2020. During the past decade, the carbon intensity of the Guangdong Province has decreased by 40.2%, respectively, which will successfully achieve the goal of reducing China's carbon intensity by 60–65% by 2030.

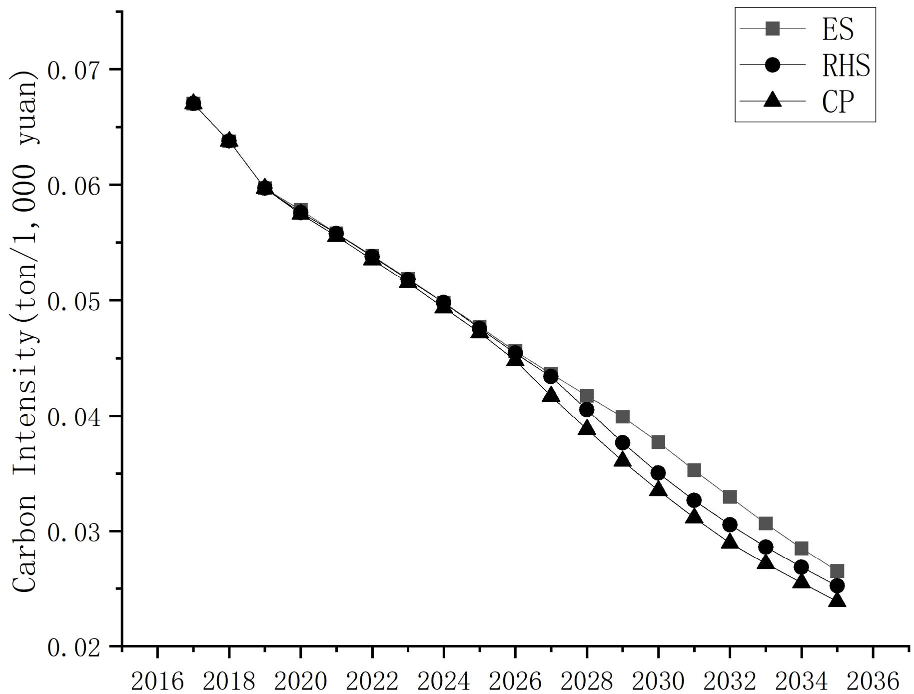

Figure 10. Carbon intensity change in different scenarios.

4.6. Changes in Investment by Sector

The model assumes that the total investment of the whole society will be the same by 2035 under each scenario, but the investment sectors of the two scenarios will change under different peak times. The annual investment was composed of the savings of the previous year and the new investment of the current year. The total annual investment increased from 3994 billion yuan in 2018 to 8244 billion yuan in 2035. Figure 11 shows the change in investment in the RHS and CP scenarios in 2035 compared with the ES scenario. Under the RHS scenario, investment will be more shifted to cement, electricity, ceramics, steel, paper and other sectors with high emissions per unit of added value, while the investment in chemical industry, construction industry and agriculture will be reduced. Compared with the ES scenario, the RHS scenario will promote investment in green transformation of cement, power, ceramics, steel and other sectors, reduce the cost of carbon reduction in the industry, and reduce the investment in chemical, construction, agriculture, glass and other sectors. Since the cost of carbon reduction in these sectors is low, the investment will be reduced under the looser carbon limit. Under the CP scenario, it will further increase the investment in the cement sector with strict carbon restrictions, reduce the investment in industries such as chemical industry and petrochemical industry, and optimize the cost of carbon emission reduction in the whole society.

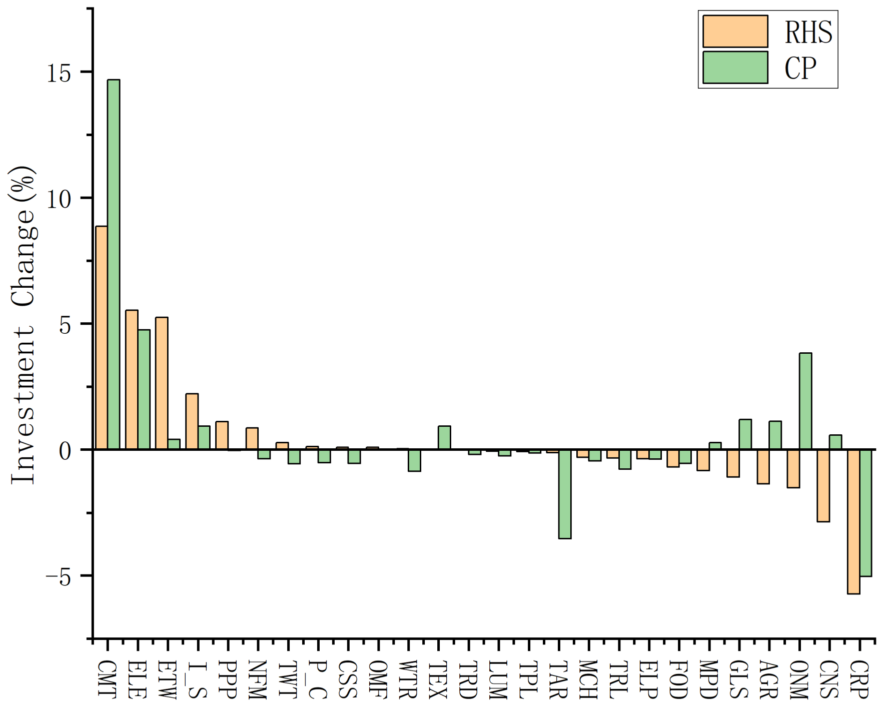

Figure 11. Investment Change under RHS and CP scenario compared with ES scenario.

4.7. Cluster Analysis of Added Value, Carbon Emissions and Employment

According to the relationship between added value, carbon emissions and employment in ES scenario 2030 has been shown in Figure 12. The sectors with low carbon emissions per unit of added value were electronic information, service industry, food manufacturing, agriculture and machinery manufacturing, while the sectors with high carbon emissions per unit of added value were power, cement, ceramics, steel, iron and petrochemical industries. From the perspective of employment impact, machinery manufacturing, service industry, agriculture, food manufacturing and road transportation were the sectors with higher unit added value employment, while electricity, petrochemical, cement, gas production and air transportation were the sectors with lower unit value-added employment. Therefore, the lower left corner of the figure should belong to the sectors that should be encouraged to develop. These sectors can not only promote employment, but also have lower carbon emissions and greater contribution to the economy.

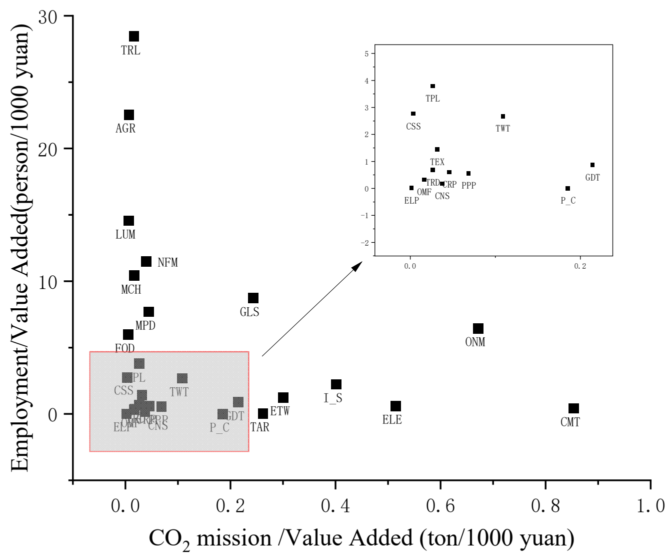

Figure 12. Cluster analysis of value added, carbon emissions and employment in ES scenario.

4.8. Sensitive Analysis

Since all of the elasticities in CES functions in the production block are given with a kind of subjectivity, we need to test the impact of these elasticities on the results. This paper changes all of these elasticities with a 5% increase or a 5% decrease and then re-runs the model again. Table 6 reports the changes in the critical variables in the research. This paper finds that the reduction in elasticity will reduce coal consumption and reduce the share of renewables. High elasticity will bring higher welfare, economic output, and carbon emissions. High energy efficiency will bring higher GDP and reduce employment and carbon emissions. Therefore, we believe that the results listed in this paper have a certain robustness.

Table 6. Sensitivity analysis.

		2030			2035		
		ES	**RHS**	**CP**	**ES**	**RHS**	**CP**
Elasticity −5%	GDP	−0.01%	0.00%	−0.01%	−0.01%	0.00%	−0.01%
	CO_2 Emission	−0.04%	−0.04%	−0.04%	−0.05%	0.00%	−0.03%
	Employment	−0.02%	−0.02%	−0.02%	−0.02%	−0.02%	−0.02%
	Investment	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Elasticity +5%	GDP	0.00%	0.00%	0.00%	0.00%	0.00%	0.01%
	CO_2 Emission	0.04%	0.04%	0.04%	0.04%	0.00%	0.03%
	Employment	0.02%	0.02%	0.02%	0.02%	0.02%	0.02%
	Investment	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
EEI −5%	GDP	−0.32%	−0.27%	−0.30%	−0.37%	−0.37%	−0.34%
	CO_2 Emission	−0.47%	0.67%	0.39%	−0.48%	0.06%	0.62%
	Employment	0.17%	0.10%	0.14%	0.17%	0.18%	0.15%
	Investment	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
EEI +5%	GDP	0.27%	0.25%	0.26%	0.34%	0.35%	0.30%
	CO_2 Emission	0.45%	−0.63%	−0.12%	0.54%	−0.09%	−0.72%
	Employment	−0.07%	−0.05%	−0.06%	−0.12%	−0.13%	−0.09%
	Investment	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

4.9. Discussion and Limitation

The CGE model is a macro-economic model based on general equilibrium theory to achieve regional Pareto optimization. Its assumption is that multiple markets are completely cleared and meet macro closure, and the information of producers and consumers is transparent, so as to maximize the benefits of producers and minimize the costs of consumers. Therefore, the CGE model assumes a perfect market, complete information and rational behavior of all market participants, which deviates from the actual production and consumption. In a real scenario, information asymmetry and irrational behavior will lead to intermediate loss and increase the social operation cost, which will lead to certain deviation between the real scenario and the simulation in CGE model. However, the CGE model can better describe the economic relations between departments, especially the joint effects of carbon restrictions on the upstream and downstream of the industrial chain. We can use the CGE model to quantitatively describe the impact of carbon constraint policies in Guangdong Province, so as to obtain policy enlightenment.

This study was also compared with other similar studies using the CGE model to simulate the impact of achieving carbon peak and carbon neutralization target on macro-economy. Generally speaking, a strict carbon restriction policy will lead to GDP loss of 2.3% to 10.9% in 2050 [38]. In this paper, compared with ES scenario, strict carbon restriction policy will lead to GDP loss of −0.2% to 0.1%. In previous literature studies, the general benchmark scenario is the unconstrained scenario, so the sector will generate GDP loss after being restricted. The benchmark scenario in this paper is a restricted scenario, which is more in line with the reality than other literatures. Through the policy of restricting high emissions industries and promoting renewable energy, the economy will gradually produce a positive effect due to investment transfer.

As the demand for residential buildings and public buildings will not increase significantly, the future growth rate of the construction industry and real estate will decline, which will affect the steel and cement industries. Meanwhile, the steel and cement industries will have prominent overcapacity problems, and will face the problems of high emissions industrial control and capacity reduction. Therefore, the carbon restriction policy to control the high emissions industries are consistent with this trend. However, the investment structure will develop to renewable energy power generation, electric vehicles, communication technology and other strategic and emerging industries, which will bring about the win-win effect and results of economic development and carbon emission reduction.

The CGE model is based on the General Equilibrium Theory, however, many industries in the actual economic society are not completely balanced. In this dynamic general equilibrium model, the savings in the previous year will be converted into the total investment in the next year. The model superimposes external policy shocks according to the historical production and consumption structure. By iterating the changes in demand and production year by year, it depicts the changes in demand, macro-economy, employment, energy consumption and carbon emissions of the Guangdong Province under different policy shocks, and will be pushed forward year by year to 2035. Therefore, in the process of forecasting with this model in the future, we need to constantly revise the elasticity coefficient to better fit the real world.

5. Main Conclusions and Policy Recommendations

5.1. Conclusions

By constructing a Dynamic CGE model (ICEEH-GD) in the Guangdong Province, this study analyzes the impact of Guangdong's security development and restriction of the high emissions industries on Guangdong's energy, carbon emissions, macro-economy and employment.

The main conclusions were as follows:

(1) Under the security development (ES) scenario, the whole society will reach its carbon peak in 2029, with a peak of about 682 million tons. Under RHS scenario and CP scenario, the carbon emission peak will be advanced to 2027 and 2025, respectively, which is 11 million tons and 21 million tons lower than the carbon emission peak in ES scenario. In terms of energy structure, RHS and CP scenarios have further optimized the energy structure. The total power consumption of terminals under RHS and CP scenarios will increase by 2.89% compared with ES scenario.

(2) By 2035, the RHS scenario will reduce the added value of industries such as textile, papermaking, cement, ceramics, steel, and will increase the chemical industry, machinery manufacturing. Reasonably restricting the development of the high emissions industries and imposing carbon restrictions on the high emissions industries will affect GDP in the short term, causing a loss of GDP. The GDP loss of the whole society from 2028 to 2034 will increase by 8 billion yuan compared with the ES scenario by 2035. Through industrial transfer, it is beneficial to the economic development of the Guangdong Province in the long run.

(3) The employment of the whole society under the RHS scenario and the CP scenario will increase by 10,500 and 104,000 jobs compared with the ES scenario by 2035. Compared with the ES scenario, the employment in the RHS scenario will shift more from power, cement, construction, ceramics and other non-metallic industries to agriculture, electronic information, service industry, machinery manufacturing, food manufacturing and other industries.

(4) The total investment of the Guangdong Province will increase from 3994 billion yuan in 2018 to 8244 billion yuan in 2035. The electronic information and machinery manufacturing industries need to further invest and develop. Cement, steel and ceramics should be encouraged to improve the quality and efficiency of their respective industries.

5.2. Policy Recommendations

Through the simulation of the renewable energy policy, restricting high emissions industries policy, and the carbon quota optimization allocation policy by the model, the comprehensive application of the policy can reach carbon peak earlier, reduce the carbon reduction cost, and promote the industrial structure transition and employment. The following policy suggestions are:

(1) The development of renewable energy can promote the increase in investment in the power sector, promote cleaner energy supply, and reduce the carbon emissions of power consumption of terminal enterprises.

(2) Expand the scale of carbon trading market and promote the reduction in carbon costs in the whole society. In particular, transportation, service and other industrial sectors should be included in the carbon market.

(3) Increase investment in low energy consumption industries with high added value, such as the electronic information, machinery manufacturing and other industries. Increasing investment in these industries can promote economic growth on the one hand and reduce the carbon emission intensity of the whole society on the other.

(4) Under the condition of ensuring the energy supply security and achieving the carbon peak in a stable and orderly manner, the application of information technology should be strengthened.

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